Customisation in manufacturing: The use of 3D printing

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Abstract[1]. An increasing demand to provide customised products creates challenges for manufacturing organisations. This poses a need to understand the characteristics required for manufacturing systems to handle customisation. In this study, 3D printing technology is assessed as an enabler for customisation. Additionally, the requirements of manufacturing systems with respect to configuration and control co-ordination are explored. A demonstrator is implemented to integrate 3D printing with conventional manufacturing, using an agent based distributed control system that co-ordinates the customisation of products and the order management.

1 Introduction

Dynamic changes in customer requirements and preferences are driving the needs for highly customised products [1]. This customer-oriented focus allows organisations to stay competitive in the global market and to satisfy varying customer demands. This requires manufacturers to deliver high variety of products, individually designed at a low cost [2]. Nevertheless, the need for a high degree of customisation creates disruptions in the manufacturing system and poses problems in scheduling. As a result, manufacturing systems are required to be flexible and resilient to disruptions [7]. Additionally, customisation leads to small batch sizes and requires frequent and dynamic re-configuration of the manufacturing system. This creates additional burden on the control system to dynamically alter process

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[1] This is a machine-readable rendering of a working paper draft that led to a publication. The publication should always be cited in preference to this draft using the following reference:

- Srinivasan, R., Giannikas, V., McFarlane, D., Ahmed, M.: Customisation in manufacturing: The case of 3D printing *in* Proceedings of the 6th Workshop on Service Orientation in Holonic and Multi-Agent Manufacturing, Lisbon, Portugal (2016).

steps and change tools, routing and material handling. Therefore, a manufacturing system should be able to handle rapid changes and product variety utilising flexible resources and intelligent control.

In this paper, the ability of 3D-printing as an enabler to handle customisation is explored. The configurations to integrate 3D printing technology with conventional manufacturing systems are proposed. A distributed agent based control system is implemented in a laboratory system to demonstrate the applicability of 3D printing in handling customisation in a conventional manufacturing system.

2 Manufacturing systems supporting mass customization

Mass customisation can be defined as the ability to deliver a wide range of products that meet specific requirements of individual customers, at a cost equivalent to mass production [1, 2]. Generally, the ability to provide mass customisation requires manufacturers to have flexible resources that can handle product variety and have the ability to change over quickly. In this section we review such requirements and we argue on the suitability of 3D printing to support mass customisation.

2.1 Handling customisation in manufacturing

In order to handle the issues related to customisation, the following characteristics of the manufacturing system are required [1, 2, 5]:

R1 – Customer driven manufacturing: The customer needs to be involved in the specification, design and manufacture of the customised parts. Generally, two options exist here. Firstly, the customer can specify the requirements and preferences of the product and the manufacturer focuses on design and production. Alternatively, the customer can himself design the product or parts and provide the design to the manufacturer to produce the product. In both instances, the manufacturing system should have the ability to handle this.

R2 – Integration of design and manufacturing systems: Involvement of customers in the design process requires seamless integration of design and manufacturing systems to quickly transition from design to manufacture. The decoupling point of order, the point where customer influences the manufacturing process, varies depending on the level of customisation or customerisation offered. This requires better integration of Computer Aided Design (CAD) and Computer Integrated Manufacturing (CIM), which will allow in ease of customised manufacturing.

R3 – Flexibility: The manufacturing system should be flexible enough to make a wide range of product variations and the resources should have multiple capabilities to handle this. Furthermore, the manufacturing system should have process/material flow flexibility to handle various customisation aspects.

R4 – Management of inventory of great variety: High degree of customisation creates a wide range of product variety and this leads to increasing levels of inventory to tackle the uncertainty with regards to customer preferences. Therefore, the manufacturing systems should have the ability to minimize inventory levels whilst handling customisation requests.

R5 –Management of customised orders: Customisation leads to varying order due-dates and reduced batch sizes. Additionally, the customer orders might arrive at random times. This requires the manufacturing system to have the ability to manage the orders by rescheduling dynamically and to have the capability to handle rush orders.

In order to address these requirements, the following are needed:

- Flexible resources with capability to make or handle customised parts
- Manufacturing system configuration able to utilise the flexible resources
- Control system for co-ordinating customised orders and flexible resources

In this paper, 3D printers enabling rapid, additive manufacturing are evaluated as an example of a flexible resource for handling customisation issues. This is discussed more in the following section. Subsequently, we discuss the configuration and co-ordination issue in the section that follows.

2.2 3D printing technology enabling mass customisation

In this section, the suitability of rapid manufacturing, especially 3D printing technology, for the management of customisation disruptions is assessed. Rapid manufacturing is defined as the use of CAD-based automated additive manufacturing process for making parts that can be used as a finished product or as a component that can be assembled into a final product [6]. 3D printing technology is a form of an additive manufacturing process, where products are produced by adding layers of materials [3].

With regards to the first requirement (*R1*) the ability of 3D printing machines to directly utilise 3D models of designed products allows the customer to design his preferences related to products directly [4]. Additionally, the customers can co-design products or choose the design by other customers in a marketplace. This allows for high degree of customisation. Additionally, 3D laser scanners can be used to map the products to get a digital design of the product directly, which enable the customers to design customisation aspects directly. Furthermore, the 3D design models from the customers can be directly transferred to the 3D printer for manufacturing.

The integration of design and manufacturing system requirement (*R2*) is addressed by 3D printing as CAD drawings can be directly imported or converted into appropriate instructions for additive manufacturing automatically. This allows quick transition from design to manufacture and provides rapid customisation capabilities.

As regards flexibility (*R3*), 3D printing based manufacturing removes the tooling requirements and thereby allows components of any geometry to be manufactured in a single resource without too much change over time [4, 8]. 3D printing eliminates the need for having a wide range of tooling and the associated costs. Furthermore, multiple materials can be combined to produce a part, rather than products or parts made of homogeneous materials. Additionally, 3D printing allows for small batch sizes and there is no change over of tools, thus providing flexibility to cater for various customisation requests. Similarly, 3D printing based manufacturing offers the possibility of reducing inventory levels of customised parts as some of them can be produced on demand based on actual customer orders (*R4*).

2.3 Configurations and co-ordination for 3D printing-based customisation

There are a number of different configurations that allow the usage of 3D printers in manufacturing depending upon the level of customisation required. These different configurations will require different co-ordination capabilities to control and manage customisation requests. Three possible configurations are depicted in Figure 1.

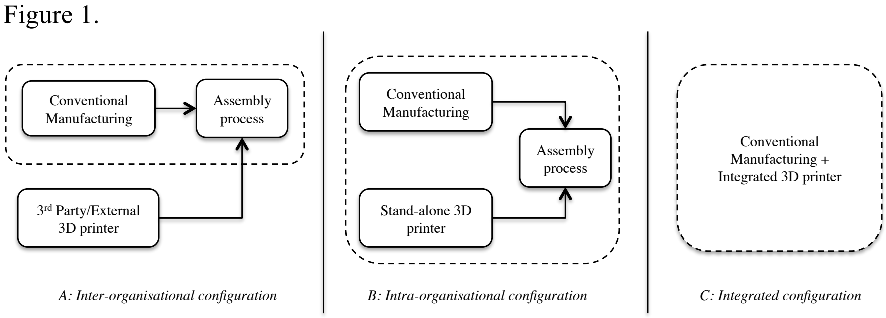

Fig. 1: Configurations for the usage of 3D printing in manufacturing

The first configuration illustrated in Fig. 1 allows 3D printed parts and components produced by printers belonging to different organisations to be used in the production of a product. These 3D printed parts are manufactured in different geographical locations and need to be transported to the location of the main manufacturer of a product for final assembly. The co-ordination needed in this case refers to the assignment of a printing job to external organisations and to the physical transportation of a part in a manufacturing line.

The second configuration describes the case where the conventional manufacturing line and the 3D printer belong to the same company. Here, conventional and flexible resources are located in the same geographical area and they are managed by the same company. However, the 3D printer is used only for making customised parts. The co-ordination aspects in this configuration are similar to the ones of the first configuration although the manufacturer will have greater control over both processes.

The third configuration depicts an integrated approach where 3D printers are part of a production line along with other resources (e.g. robots) and tools. It illustrates the case where 3D printers have seamlessly been integrated in existing manufacturing processes and are considered part of the overall manufacturing system. In this configuration, the 3D printer is also involved in the making of conventional parts as part of the manufacturing system. One of the main issues here is introducing 3D printing resources in existing systems and controlling them along with other manufacturing resources.

In order to examine the introduction of 3D printing in conventional manufacturing in more detail, a demonstrator was developed. The demonstrator uses the intra-organisational configuration as a configuration that allows a manufacturer to use 3D printing without the need to outsource to external parties (inter-organisational configuration) and without the need for significant changes in the existing manufacturing line (integrated configuration). This demonstrator is described next.

3 Demonstrator

In this section, we describe the developed demonstrator as well as our key findings in terms of meeting the customisation requirements discussed in Section 2.

3.1 Set-up

The production system used in the demonstrator produces a gearbox (Fig. 2) consisting of: i) a metal casing made of two parts, top and base, ii) a plastic top cover, iii) gears which go into the casing (metal or customisable plastic), iv) (optional) customisable cap. The customers have two options for customisation. First, the customer can have a choice of different coloured gears with different gear ratios. Additionally, the customers can prefer to have a custom made cap for the gearbox with added text.

The production system for manufacturing the gear box consists of three cells. Cell 1 is a manufacturing cell, where the metal casing is machined by a 5-axis CNC machine and the plastic part is formed by a vacuum forming machine. Cell 2 is the sub-assembly process where the metal top and the plastic cover are aggregated. Cell 3 is the final assembly cell associated with gear meshing and fastening operations. The customised parts (i.e. gears and cap) are printed and delivered in Cell 3 by a standalone 3D printer.

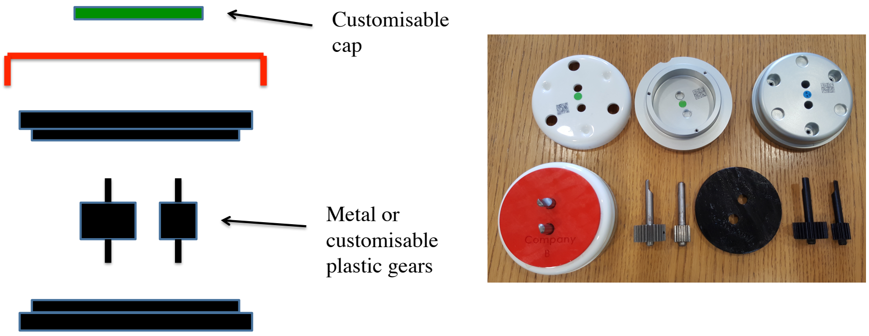

Fig. 2: Gear box

3.2 Implementation

This section illustrates how the three key essential features required for handling customisation, discussed previously are implemented.

Firstly, a 3D printer is used as the flexible resource to make the customised parts (i.e. gears and caps), which delivered to Cell 3 and are integrated into the final product. The use of 3D printing allows easy transition from design to manufacture and offers additional flexibility by removing the change-over time between products. Furthermore, the use of 3D printers eliminates the need to have customised parts being maintained as inventory.

With regards to configuration, Figure 3 shows the configuration implemented in the demonstrator. The 3D printer is implemented as a stand-alone resource that is dedicated to making customised parts only (i.e. intra-organisational configuration). Cell 1 and cell 2 are conventional manufacturing systems which deliver the metal base and the sub-assembly (metal top and plastic cover) to Cell 3. The 3D printer delivers customized parts to cell 3 to be integrated into final assembly.

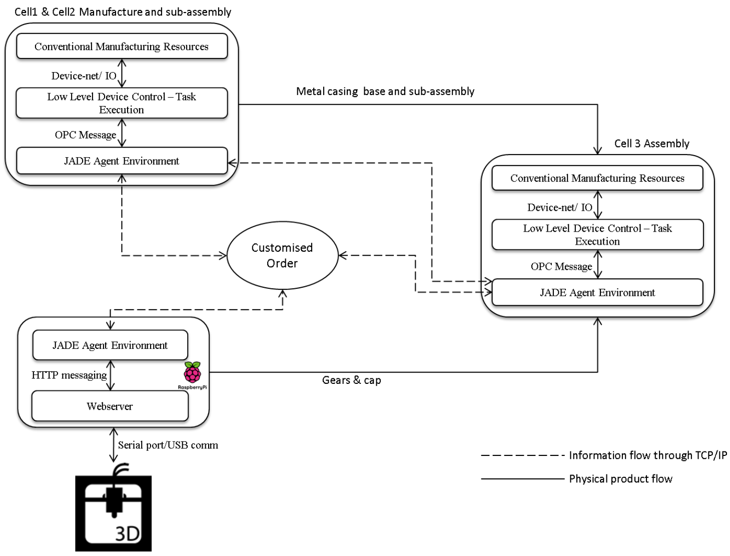

Fig. 3: Demonstrator configuration and control

For co-ordination between the conventional manufacturing and the 3D printer, a distributed control system was implemented. The distributed control was based on multi-agent systems and was implemented using the JADE framework (see fig. 3). The agents and their roles in co-ordination are:

- Order agent: Responsible for negotiating the task allocation with the various manufacturing resources. Additionally, the orders will have the customisation requests associated with a design file. The order agent then negotiates and reserves the job with the 3D printer.
- Customisation agent: This agent represents the 3D printer and is responsible for managing customisation request and for scheduling the printing operations based on order due dates.
- Resource agents: These agents represent the typical manufacturing resources such as CNC machine and robots for material handling. These agents are responsible for managing task allocation and order management.

The stand-alone 3D printer is implemented as an intelligent resource capable of making its own decision with respect to customisation and scheduling. This is enabled by having a Raspberry Pi computer integrated with the 3D printer. The integrated computer then has the capability to receive and process messages from the orders, and also control the additive manufacturing process.

3.3 Meeting customisation requirements

We conclude this section with a discussion on the way the five customisation requirements identified in Section 2 have been met in our demonstrator. These are summarised in Table 1.

Table 1. Customisation requirements implemented in demonstrator

Requirements	Implementation
Customer driven manufacturing	The customers can decide the choice of options for the gears and ratios, along with the optional customised caps. The manufacturer has the required design in CAD which is then transferred to the 3D printer for printing.
Integration of design and manufacturing systems	3D printer is directly linked to the manufacturing system. Orders are associated with the required design information and are transferred directly to the 3D printer, which converts the design into appropriate commands for printing the parts.
Flexibility	3D printer can print both customised gears and caps from the same resource, thereby offering flexibility to use a single resource for all customisation needs.
Management of inventory of great variety	The ability to make parts quickly and on request eliminates the need to hold inventory. Additionally, the customised parts can be produced from a single material, thereby reducing the complexity and level of inventory needed.
Management of customised orders	Intelligent orders and resources having distributed decision making ability allow the orders to negotiate and schedule tasks independently. This provides flexibility to handle small batch sizes and re-schedule dynamically to cater for rush orders on customisation.

4 Conclusions

In this paper we investigated the suitability of 3D printing to handle customisation needs. 3D printing was chosen as a technology providing flexible and rapid manufacturing capabilities. Our analysis shows that the technology can indeed be used for enhancing the customization capabilities of conventional manufacturing systems. Nevertheless, the integration of 3D printing with conventional manufacturing systems poses challenges in:

- Automation: Lacks ability to automatically transfer materials in and out of the 3D printer. In-process sensing of product quality is not well developed.
- Communication: Existing 3D printers have different communication interfaces (e.g Ethernet, serial port) and are not inter-operable with standard manufacturing devices (e.g. PLC).

- Interfaces: There is limited control interfaces to monitor and execute tasks in 3D printers. Ability to control and communicate with 3D printers varies between manufacturers (open source vs proprietary tools). Furthermore, the conversion of CAD files into machine codes are not standardized.

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